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Renewable and Sustainable Energy Reviews
9 (2005) 638–645

RENEWABLE
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ENERGY REVIEWS

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Exergy analysis of domestic-scale solar water heaters

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Received 13 November 2003; accepted 7 April 2004

Abstract

Solar water heater is the most popular means of solar energy utilization because of technological feasibility and economic attraction compared with other kinds of solar energy utilization. Earlier assessments of domestic-scale solar water heaters were based on the first thermodynamic law. However, this kind of assessment cannot perfectly describe the performance of solar water heaters, since the essence of energy utilization is to extract available energy as much as possible. So, it is necessary to evaluate domestic-scale solar water heaters based on the second thermodynamic law.

No matter the technology process, from the property of energy utilization perspective, we can separate the technology process into three intimately related sub-procedures, namely conversion procedure, utilization procedure, and recycling procedure. An energy analysis entitled 'Three Procedure Theory' can be conveniently conducted as presented by Professor Hua Ben. Compared with other theories of energy analysis, three procedure theory exhibits great advantages. The utilization procedure puts forth requirement for the design of parameters in conversion procedure and sets up limits in the consideration of recycling procedure. Of course, under specific conditions, the utilization procedure also receives feedback from other procedures. Three procedure theory furnishes us a good platform to perform energy analysis.

The study in this paper is based on three procedure theory. Exergy analysis is conducted with the aim of providing some methods to save cost and keep the efficiency of domestic-scale solar water heater to desired extent and at the same time figuring out related exergy losses. From this survey, it is shown that for an ordinary thermally insulated domestic-scale solar water heater, D_{ju} (exergy losses due to imperfectly thermal insulation in collector) and D_{jR} (exergy losses due to imperfectly thermal insulation in storage barrel) cannot be avoided. D_{ku} (exergy losses due to

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1364-0321/$ - see front matter
doi:10.1016/j.rser.2004.04.007

irreversibility in collector) is mainly caused by irreversibility of heat transfer and D_{kR} (exergy losses due to irreversibility in storage barrel) is dominated by the mixing of water at different temperature. D_{ku} acts as the driving force for the system while D_{kR} is of little contribution. A good design of storage barrel with little D_{kR} will go a long way in improving exergy efficiency. An equation for computing D_{kR} is presented. For the collector, which is the core of the domestic-scale solar water heater, a judicious choice of width of plate W and layer number of cover is necessary. We define collector exergy efficiency η_{xc} to be $\eta_{xc} = E_{xo}/E_{xu}$. The relation between collector exergy efficiency and width of plate together with layer number of cover is also analysed.

Keywords: Domestic-scale solar water heater; Exergy; Three procedure theory

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1. Introduction

Earlier, in order to sustain growth of economy, mankind had evolved in a way, which contradicted with sustainable development. The present modern society is constructed upon excessive energy consumption. People took it for granted that energy resources were inexhaustible, but fortunately now they have revised their opinion. The fact that non-renewable energy resources will be available at the present usage level only for a limited period has been accepted worldwide. The world's total oil reserves will be depleted in early 21st century. Natural gas can be of use to people 20 years more than oil. Coal will last for another 200 or 300 years. However, there are many more crises. Environmental problems due to people's blind exploitation and utilization of resources are severely threatening our subsistence. As a consequence, the need for renewable energy resources becomes very urgent. As an absolutely clean energy, solar energy is of most importance and has been most emphasized on so far.

Solar water heater technology is a method of solar energy utilization technology. It has been well developed and can be easily implemented at a low cost. Earlier studies on

Nomenclature

E_u	energy from sun (input energy) (W)
E_{xu}	exergy from sun (input exergy) (W)
E_o	energy from collector to storage barrel (W)
E_{xo}	exergy from collector to storage barrel (W)
E_E	energy from storage barrel to end-user (output energy) (W)
E_{xE}	exergy from storage barrel to end-user (output exergy) (W)
E_L	energy losses due to imperfectly thermal insulation in collector (W)
D_{ju}	exergy losses due to imperfectly thermal insulation in collector (W)
E_j	energy losses due to imperfectly thermal insulation in storage barrel (W)
D_{jR}	exergy losses due to imperfectly thermal insulation in storage barrel (W)
E_R	energy from storage barrel to collector associated with water recycle (W)
E_{xR}	exergy from storage barrel to collector associated with water recycle (W)
D_{ku}	exergy losses due to irreversibility in collector (W)
D_{kR}	exergy losses due to irreversibility in storage barrel (W)
T_{fo}	outlet temperature of water from collector to storage barrel (K)
T_{fi}	inlet temperature of water from storage barrel to collector (K)
T_m	average temperature of water in storage barrel (K)
$\dot{m}$	mass flow rate of water (kg/s)
C_P	specific heat of water (J/(kg °C)
T_o	ambient temperature (K)
S	transverse area of storage barrel (m^2)
T_{top}	temperature of top water in storage barrel (K)
T_{bottom}	temperature of bottom water in storage barrel (K)
η_x	exergy efficiency of domestic-scale solar water heater
η	energy efficiency of domestic-scale solar water heater
ε	grade of energy
Q	associated heat (W)
η_{xC}	exergy efficiency of collector
U_c	collector thermal loss coefficient (W/(m^2 °C)
W	distance between pipes in collector (cm)

domestic-scale solar water heaters were based on the first thermodynamic law. In fact, as we know, it is the quality of energy that is important not the quantity of energy. So, it is necessary to evaluate domestic-scale solar water heaters from the point of view of the second thermodynamic law.

An exergy analysis is conducted in this paper with the aim of providing with some ways to save cost and keep the efficiency of domestic-scale solar water heater to the desired extent and at the same time figuring out related exergy losses. The analysis is based on the three procedure theory [1] represented by Professor Hua Ben. Three procedure theory is a theory that starts with the unit process analysis and then further investigates the exergy and energy flows in the light of the total system. Based on this theory, exergeconomic method and computer technology can better exploit their potential.

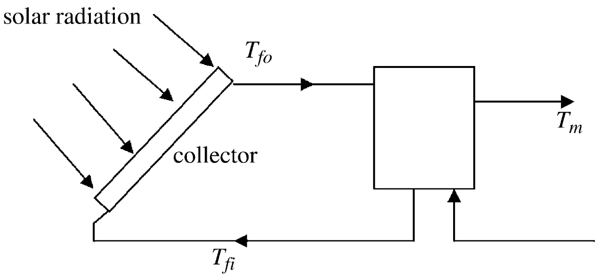

Fig. 1. A typical domestic-scale solar water heater.

2. Exergy flow in domestic-scale solar water heaters

A typical domestic-scale solar water heater is schematically illustrated in Fig. 1 [2]. Three procedure theory shows that energy conversion procedure takes places at the sun. The nuclear reaction in the sun makes it possible for the sun to emit a great quantity of power, which is transmitted in the form of electromagnetic waves. Energy utilization is carried out in the collector. Solar radiation penetrates the cover and is incident on the black-colour plate where it heats water flowing through the pipe. Energy recycling procedure corresponds to the storage barrel. Hot water go is pumped to end-users at temperature T_{m} and cold water fills the storage barrel from the bottom pipe simultaneously. A three procedure theory model of domestic-scale solar water heater is shown in Fig. 2.

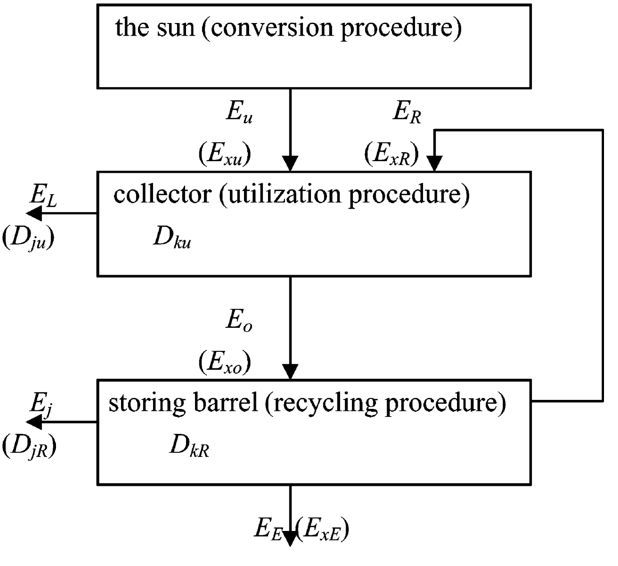

Fig. 2. The three procedure theory model of domestic-scale solar water heater.

Energy balance equations in this model are:

$E_u + E_R = E_L + E_o$
$E_o = E_j + E_E + E_R$
Exergy balance equations in this model are:

$$E_{xu} + E_{xR} = D_{ju} + E_{xo} + D_{ku}$$

$$E_{xo} = D_{jR} + E_{xE} + E_{xR} + D_{kR}$$

The change in kinetic exergy in utilization procedure is negligible since most domestic-scale solar water heaters are driven by the difference of density of water, namely no great decrease in pressure is involved, so we can use the following equation to calculate E_{xo}.

$$E_{xo} = \dot{m}c_p(T_{fo} - T_o) - \dot{m}T_o c_p L_n \frac{T_{fo}}{T_o}$$

3. Case study

To simplify the calculation in equations, we consider the case in which hot water stored in the barrel is only consumed at night. The whole-day testing results for domestic-scale solar water heaters, conducted by Domestic-Scale Solar Water Heaters Performance Testing Station, located in Yun Nan province, China, show that the case with 50 °C top hot water temperature and 38 °C bottom hot water temperature in storage barrel under the conditions of 2.5 m^2 of collector area, 25 °C average ambient temperature, 24 °C average ambient water temperature, 466 J/(m^2 S) of whole-day average solar radiation, 196.4 kg of water storing log capacity for the storage barrel is quite general for domestic-scale solar water heaters which are prevalent in the Chinese market [3]. Assuming the temperature distribution in the storage barrel is linear, we get:

$$\begin{aligned} E_{xE} &= \int_0^L c_p \rho s \left(\frac{T_{top} - T_{bottom}}{L} x + T_{bottom} - T_o \right) dx \\ &\quad - \int_0^L c_p \rho s T_o L_n \frac{((T_{top} - T_{bottom})/L))x + T_{bottom}}{T_o} dx \\ &= mc_p \left(\frac{T_{top} + T_{bottom}}{2} - T_o \right) - mc_p T_o \left(L_n \frac{T_{top}}{T_o} - 1 \right) \\ &\quad - \frac{T_{bottom} T_o mc_p}{T_{top} - T_{bottom}} L_n \frac{T_{top}}{T_{bottom}} \end{aligned}$$

We define exergy efficiency of the domestic-scale solar water heater as $\eta_x = E_{xE}/E_{xu}$ [4,5]. Substituting values presented above for the associated variables yields: $\eta_x = E_{xE}/E_{xu} =$ 0.77%. The energy efficiency defined as $\eta = E_E/E_u$ equals 15.1%. So there is a great difference between η_x and η. The low exergy efficiency can be understood by the fact the output energy of domestic-scale solar water heater is of very low quality.

Since only thermal exergy is involved, the grade of energy ε is $1 - T_o/T$. The relation between ε and heat Q associated is seen in Fig. 3.

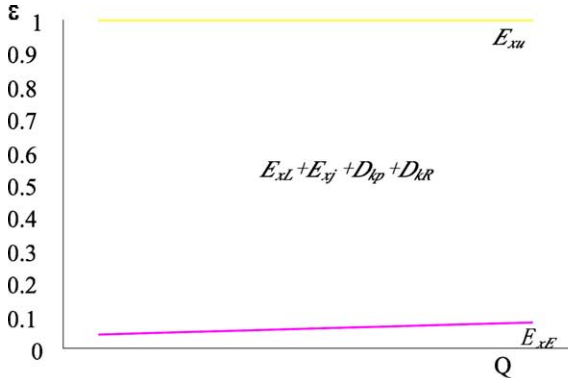

Fig. 3. The relation between ε and heat Q associated.

The area between curves E_{xu} and E_{xE} in Fig. 3 can be geometrically interpreted as the total exergy losses occurring in this system. For an ordinary thermally insulated domestic-scale solar water heater, D_{ju} and D_{jR} cannot be neglected. D_{ku} is mainly caused by irreversibility of heat transfer and D_{kR} is dominated by the mixing of water at different temperatures. D_{ku} acts as the driving force of the system, while D_{kR} is of little use. A well-planned design of storage barrel with little D_{kR} will vastly improve exergy efficiency.

D_{kR} can be calculated by $QT_{\mathrm{o}}(T'_{\mathrm{H}}-T'_{\mathrm{c}}/T'_{\mathrm{H}}\times T'_{\mathrm{c}})$. $T_H{}'$ and $T_c{}'$ are the arithmetic average value between the original and final temperature for the hot fluid and cold fluid, respectively. Q is the heat transferred from the hot fluid to the cold fluid. Assuming the temperature distribution in the barrel is linear and dividing the barrel into $2N$ portions of equal volume, we approximate the exergy loss due to the mixing in the barrel as the following

$$D_{\mathrm{kR}}=\lim_{N\to\infty}\sum_{j=2k+1}^{N}\frac{c_{\mathrm{p}}mg^2}{8N\left(T_{\mathrm{top}}-\mathrm{gj}-\frac{g}{4}\right)\left(T_{\mathrm{top}}-\mathrm{gj}-\frac{3g}{4}\right)},\quad k=0,1,2,3\ldots$$

where g is the temperature gradient in the barrel, and m is the total mass of water stored in the barrel.

4. The effects of collector design parameters on the collector exergy efficiency

In a collector, the most important design parameters are the width of plate W corresponding to the thermal transferring performance and the property of cover related to the thermal loss. Here we define collector exergy efficiency η_{xc} to be $\eta_{\mathrm{xc}}=E_{\mathrm{xo}}/E_{\mathrm{xu}}$. In this sector, we choose the non-decision making variables as the following: the area of the collector is 2.59 m^2, solar radiation is 466 J/(m^2 s), mass flow is 0.015 kg/s, ambient temperature is 25 °C, heat exchange coefficient between the fluid and the pipe is 300 W/(m^2 °C). Fig. 4 is the plot of collector exergy efficiency η_{xc} versus the width of plate W under three collector thermal loss coefficient U_{c} (2, 4, 8 W/(m^2 °C)), which

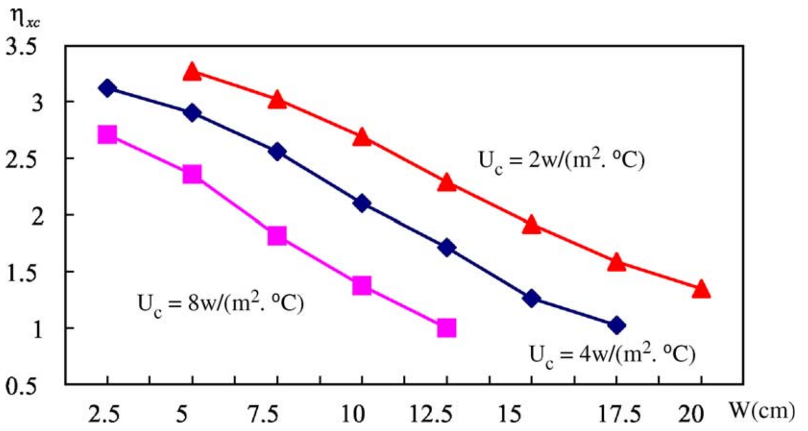

Fig. 4. The width dependence of collector exergy efficiency for three kinds of cover design.

represent three kinds of cover design: one layer, two layer, three layer cover with transparent non-selective coat, respectively.

We can observe the trend between η_{xc} and W and U_c. η_{xc} decreases with W and U_c. If we expect a higher η_{xc}, we must design a smaller W and U_c using a larger investment. In fact, almost half of the total investment of domestic-scale water heater is assigned to the collector. The area of the collector is proportional to investment. It is impractical to make a collector with three or more layers of cover and very small width of plate. We recommend that two layers of cover and width of the plate ranging from 5 to 10 cm would be a good choice.

5. Conclusion

An exergy analysis is shown in this paper. The exergy efficiency of domestic-scale water heater is small as the output energy is of low quality. Large exergy losses occur in the storage barrel. It is worthwhile to design a new style of storage barrel to reduce unnecessary mixing of water. To improve the exergy efficiency of domestic-scale water heater, a judicious choice of width of plate W and layer number of cover is necessary. It is also necessary that we carefully weigh our choices between exergy efficiency of domestic-scale water heater and cost.

Acknowledgements

The authors greatly benefited from discussions with and comments by Professor Hua Ben and Li Zhihong. All remaining errors are mine.

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